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The research projects described herein derived computational support from a color graphics workstation provided to the University of New Mexico, Department of Mechanical Engineering, through an equipment grant under the Infrastructure Support Program for Historically Black Colleges and Universities and Minority Institutions (HBCU/MI's). The project topics, faculty investigator and support include:

1) Finite element modeling of suspension flows, Prof. Marc Ingber;
2) Finite element simulations of failure mechanisms in quasi-brittle materials and fiber-reinforced ceramics, Prof. Howard L. Schreyer; AFOSR Grants 91-0419 and F49620-95-1-0262;
3) Dynamical system predictions and measurements of turbulent shear flows for the study of optical propagation through turbulence, such as occurs in aero-optics problems; Prof. C. Randall Truman, AFOSR Grants 91-0071 and F49620-94-1-0140.

Details on the publications, personnel supported and interactions may be obtained from the technical reports for each grant.

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# WORKSTATION FOR SUPPORT OF BASIC RESEARCH (HBCU/MI/INFRA PGM)

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# FINITE ELEMENT MODELING OF SUSPENSION FLOWS

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In recent years the research community has devoted some effort to the modeling of particle suspension flows using a continuum approach. Phillips et al. (1991) have presented a phenomenological constitutive model of shear-induced particle migration in suspension flows. Because particle suspensions are used in numerous manufacturing processes of direct interest to SNL, we have begun work in trying to model these problems numerically. An existing SNLA two-dimensional finite element computer code, NACHOSII, has been modified to incorporate the equations which govern particle migration in suspensions.

In the past there has been but one successful implementation of particle migration models in the context of finite element method. This prior implementation was an explicit formulation for a pipe flow problem, but our present work is based upon an implicit formulation. Having implemented the Phillips model of shear-induced particle migration, we have spent some time during the past few months trying to benchmark the code. To date we have looked primary at simulations involving wide-gap Couette devices. These problems have been chosen primarily because experimental NMR data is available for these cases.

## Concentric Couette Simulations

Two benchmark simulations of concentric wide gap Couette devices were performed. Details concerning the problem geometry, material and flow parameters, and analytic solutions can be found in Phillips et al. (1991). Because it is not possible to model these problems as strictly steady-state, simulations are performed as transient evolutions from an initial configuration. Figures 11 and 12 summarize the result of two problems studied for initial particle volume fractions of 50% and 55%. The results of the numerical simulation indicate good correlation with both the analytic results of Phillips and appear to fit the experimental data best in the center portion of the flow. The material and flow parameters for the models were taken directly from Phillips and no attempts were made to adjust these values to provide a better fit.

## Eccentric Couette Simulations

A benchmark simulation was performed on a wide gap couette device in which the inner cylinder is offset from the outer cylinder center. Unlike the case of the rotating concentric cylinders, no analytic solution exists for the steady-state particle distribution in the problem of rotating eccentric cylinders. Details concerning the problem geometry, material and flow parameters, can be found in Phan-Tien et al. (1995). One numerical simulation was

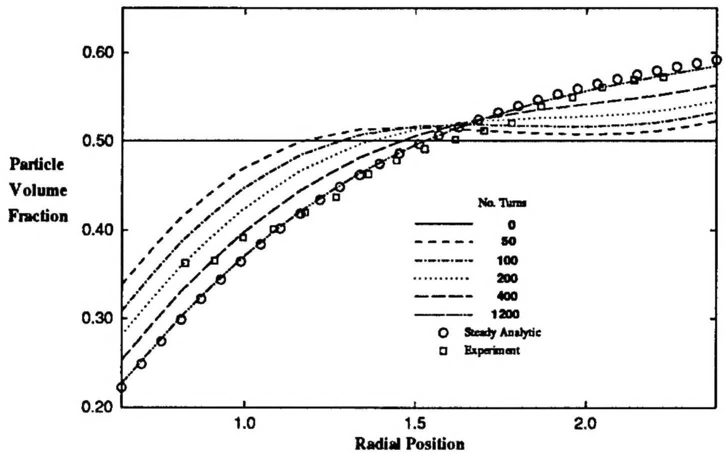


Figure 1: Particle distribution in concentric Couette, initial volume fraction 50%

performed for an eccentricity ratio of 1/3 and an initial particle concentration of 50%. Computed results are compared with the results of experiments of experiments performed at SNLA in Figure 13. The best agreement between computed results and experiment occur in the center portion of the wide gap. Again no attempt has been made to adjust the material parameters for a better fit with experiment.

## Piston Flow Simulations

One of the common ways of displacing a suspension in a tube is with a piston. As a prelude to studying some more complex suspension transport problems, we have modeled a simple problem of suspension displacement between two pistons. Simulations were carried out for piston travel to diameter ratio of 10. Qualitatively, the computed results are found to bear some resemblance with the experimental NMR images near the pistons. However, the center region between the two pistons have yet to be imaged, and will later be compared with the computed results.

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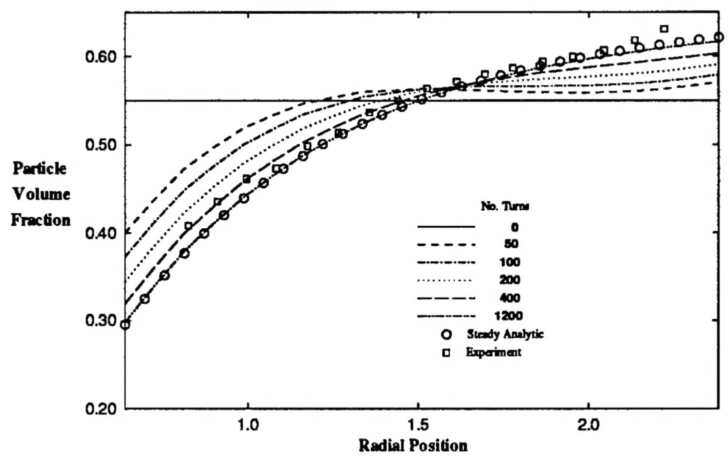


Figure 2: Particle distribution in concentric Couette, initial volume fraction 55%

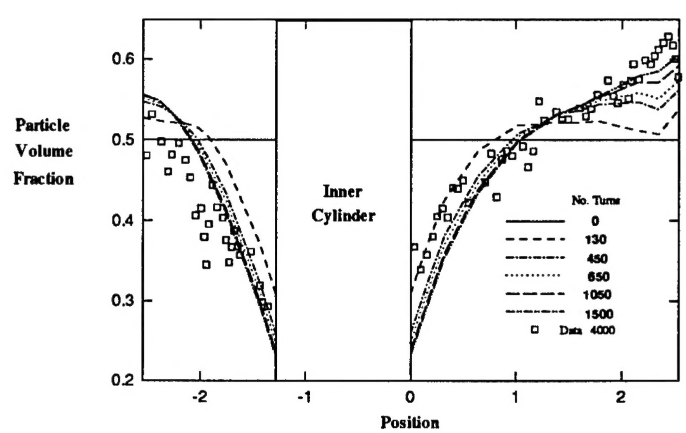


Figure 3: Particle distribution in concentric Couette, initial volume fraction 55%

# Applications of the HP Workstation to Problems Involving Large Deformations and Material Failure

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One of the proposed tasks for which the workstation was requested involved modelling the evolution of microcracks along grain boundaries in alumina. The initial phase of this research has been accomplished and the results of the research are contained in the paper by Wang et al., (1995). The ability to use the workstation was an essential ingredient in conducting the numerical part of the research in which it was predicted that microcracks can develop and, with continued loading, some microcracks close up while others evolve to macrocracks. Such features were also shown in the experimental phase of the research.

In joint work with Professor Sulsky of the Applied Mathematics Group at the University of New Mexico, a new computational algorithm (material point method) has been developed for analyzing the large deformations of solids (Sulsky et al., 1994, 1995, 1996). This capability has opened up the possibility of obtaining numerical solutions on a workstation that were previously only possible on mainframe computers. Examples of problems being considered are extrusion, metal rolling, injection molding and solidification, metal cutting, penetration, perforation, upsetting and high velocity impact. Sandia National Laboratories provided a graphics package which is particularly suitable for displaying the results from the material point method. This package has been installed on the workstation and provides the University with a unique capability of providing state-of-the-art calculations and graphical output.

The enhancement in research capability provided by the workstation has provided several opportunities for joint research with national laboratories and industry. In particular, a woman graduate student from Los Alamos National Laboratory performed a detailed study of metal cutting for a Master's thesis (Sharp, 1995). The only comparable analysis has been conducted by a Ph.D. student at a major university, an indicator that the procedure developed at the University of New Mexico competitive with much fewer resources. The same algorithm is being used as the basis for studies on metal rolling and on the inflation of airbags by Ph.D. students from Sandia National Laboratories. Recently Los Alamos National Laboratory has adopted the procedure for a study of the interaction of viscoelastic particles under high pressures.

Professors Sulsky and Schreyer recently visited personnel at the research laboratory of the Aluminum Company of America where intense interest was expressed in using the procedure for studying the compaction of aluminum particles under high temperature, a problem that is extremely difficult for conventional finite element and finite difference procedures. It was also pointed out by ALCOA that there is a great need for a procedure such as this in the design of extrusion molds.

At the University of New Mexico, the material point method is being currently used on the workstation to investigate penetration, the failure of a certain class of composites by delamination, and to study the microstructural effect of fibers on the enhancement of ductility in ceramics.

Although these research activities involve a considerable amount of basic analysis, there is no question that the presence of the workstation has been of immense benefit in providing numerical results to illustrate the applications of the theory. For example, one consequence has been that Sandia National Laboratories has loaned us another workstation to perform microstructural studies on failure mechanisms of electrical connections. In the future we see the need for large-scale calculations and with appropriate support hope to avail ourselves of the Maui High Performance Computing Center operated by the University of New Mexico for the US Air Force.

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# Optical Propagation Through a Round Turbulent Jet

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## Introduction

The effect of large-scale (or coherent) structure on optical propagation through a round turbulent jet has been studied using numerical simulations as well as experimental data. A passive scalar in the computations is related to refractive-index fluctuations, while temperature fluctuations in a heated jet were used in the experiment. Linear stochastic estimation was employed to determine the influence of the large-scale structure on the refractive-index field and thus on optical phase error and beam deflection. The importance of sharp gradients at the edges of the large-scale structure was demonstrated. Linear stochastic estimation based on three temperature probes has successfully reproduced the majority of the experimental beam deflection. When linear stochastic estimation is applied to an instantaneous realization from the large eddy simulation, velocity and vorticity at two locations are sufficient to predict the phase error through an entire ring vortex.

## Approach

The effects of turbulent structure upon optical propagation through a free shear flow are being studied by measuring and predicting the dynamics of a passive scalar in a low-Reynolds-number round jet. The experiments are carried out at the Air Force Phillips Laboratory (AFPL) in collaboration with the AeroOptics working group led by Dr. Lenore McMackin.

Linear Stochastic Estimation (LSE) has been used to analyze coherent turbulent structure in the experimental data and in numerical simulations of the round jet, for both the distorted wave front and field variables. The capability of conditional averages formed by LSE to reproduce turbulent structure relevant to optical phase distortion is being studied for the AFPL data and a low-Re numerical simulation database. The coherent structure in free shear flows is characterized by sharp interfaces caused by entrainment of fluid from one stream deep into the other. The instantaneous structure of the refractive-index field (or passive scalar) is produced by the large-scale turbulent structure. Thus the optical distortion induced in an optical beam propagating through the flow will depend directly on the dynamics of this large-scale structure. Compensation or correction of the distorted wave front will thus require detailed knowledge of the flow dynamics.

The criteria upon which conditional averages are based are being examined to determine whether LSE based on limited experimental information can adequately represent the scalar field to predict the optical distortion across the flow. Such data will include a few point measurements of velocity or temperature and the deflection of one or more thin beams propagating across the shear layer which are provided in the AFPL experiments. It has been confirmed that these few measurements can provide enough information to closely approximate the large-scale features of the optical phase distortion.

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**Progress**

We have developed an experimental turbulent jet facility at the Air Force Phillips Laboratory in which flow and optical parameters can be measured simultaneously (Truman, et al. 1994). Acoustic forcing was added to the plenum chamber to enhance vortex formation in the jet. Measurements of beam deflection through a turbulent jet for various beam diameters (or apertures) showed that maximum deflection occurs for the smallest beam diameter and verified the importance of sharp gradients at the edges of large-scale turbulent structures (Truman, et al. 1994). We have also implemented Linear Stochastic Estimation (LSE) of beam deflection for propagation through the center plane of the experimental jet flow based on 3 temperature probes within the jet shear layer (Truman, et al. 1995). Data from a large eddy simulation of a turbulent round jet which includes a passive scalar was acquired. LSE of phase error and beam deflection for propagation through the center plane of the jet based on 2 reference points within the jet structure where velocity and vorticity components are known was implemented (Barsun, et al. 1996).

Linear Stochastic Estimate (LSE). Linear Stochastic Estimation (LSE) is a simple yet powerful technique for approximating conditional averages of correlations between turbulent quantities (Adrian et al. 1989). The utility of conditional averages is that turbulent events (e.g., intermittent bursts) can be accurately identified with limited flow field information, such as velocity fluctuations at a few predetermined points in the flow. The LSE is formed from two-point spatial (or temporal) correlations between the quantities of interest, such as velocity and scalar fluctuations or even optical phase error. The LSE of a turbulent shear flow gives a remarkably good reproduction of the large-scale structure (e.g., Glauser et al., 1993). According to Adrian et al. (1989), the "unconditional spatial correlations have imbedded within them the structures of the conditional fields."

LSE of beam deflection. Three cold-wire temperature probes were placed in the jet shear layer immediately downstream of a thin laser beam propagating through the flow. After passing through the heated jet, the beam is focused on a lateral effects detector (LED) to measure its deflection. The probes as well as the beam lie on the center plane of the flow; only streamwise deflections are considered here. Probes are placed on either side of the jet to include the influence that each side of the shear layer has on the beam deflection.

Spectra from the probes and the beam deflection were used to select a forcing frequency which excited the shear layer mode of the nozzle exit boundary layer. Acoustic forcing provided by a small audio speaker in the plenum was sufficient to enhance vortex formation at this fundamental frequency.

Temporal correlations between the beam deflection and each temperature signal illustrate the differences in the structure of the temperature field detected at each probe location. Beam deflection in the streamwise direction is directly related to streamwise gradients in the temperature, which vary as vortices convect through the measurement locations. The LSE was created using the correlation between beam deflection and each of the three temperature signals with appropriate time delays. The characteristic behavior of the beam deflection was found to be predicted by the LSE very well. We are studying the selection of different time delays in the correlation as well as different probe locations at several streamwise locations.

Large Eddy Simulation. We have examined the Large Eddy Simulation (LES) of the low-Reynolds-number turbulent jet (Chen et al. 1993) to determine the relationship between the scalar fluctuations and the velocity and vorticity fields. While the scalar fluctuations can be linked to streamwise velocity fluctuations, the scalar distribution produced by the rollup of

the ring vortex is complex. Some geometric characteristics of the scalar distribution must be linked to azimuthal vorticity or radial velocity. Two-point correlations between the scalar and these three variables were computed within the first highly developed ring vortex. Each correlation was computed from an ensemble of values from around the jet at fixed azimuthal displacement $\Delta\theta$ for each ( $r$, $\Delta r$, $z$, $\Delta z$ ) since the flow is inhomogeneous in r and z. The scalar field in each plane, $\theta$ =constant, was computed by a Linear Stochastic Estimate (LSE) with two fixed reference points in the plane $\theta = 0$. Streamwise velocity, radial velocity and azimuthal vorticity at these reference points were the input to the LSE. The estimates of the scalar field were seen to be quite good over the entire spatial extent of this vortex (Barsun, et al. 1996).

**Acknowledgements**

These results are drawn from the thesis research of Brian Staveley, Hans Barsun and Tim Luna. The assistance of Dr. Jacqueline Chen (Sandia-Livermore) and Prof. Wolfgang Kollmann (UC-Davis) in providing the numerical data for the turbulent jet is greatly appreciated. The assistance of Dr. Bruce Masson, Capt. Bryan Scruggs and Dr. Lenore McMackin of the Air Force Phillips Laboratory, Albuquerque, in carrying out this research is gratefully acknowledged. The assistance of Phillips Laboratory personnel and its contractors, particularly Applied Technology Associates, was essential to the construction and operation of the turbulent round jet facility.

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